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Localized photonic modes in photonic crystal heterostructures

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ABSTRACT

In this work, interface modes of two-dimensional photonic crystal heterostructures have been investigated by usage of the supercell method. The photonic crystal heterostructure is made of two photonic crystals with square symmetry in which one of them is composed of circular dielectric rods in air background and the other one is constructed by drilled square holes in dielectric. It is shown that using of a proper supercell plays an important role in obtaining the correct interface modes. We have also showed that the guided interface modes and single mode which is different from those reported in some published works are nearly dispersionless.

1. Introduction

In the past decade there has been great interest in studies of photonic crystals which are constructed by arranging dielectric materials in a periodic fashion [1–3]. One of the most intriguing properties of photonic crystals (PCs) is the emergence of localized modes that may appear within the photonic band gaps when the periodicity of the structure is spoiled [1]. For example, these defect modes can be created inside an infinite lattice as a line defect by removal of one or several rows of atoms [4]. In fact, the interface can form between two different lattices with different physical or geometrical parameters, which can be called photonic crystals heterostructures (PCH) [5] and provide a new way to form the light waveguide [6,7]. The PCH compared to conventional PC waveguide have the advantage of offering more degrees of freedom in tuning the waveguide modes [5]. Also, PCH cavities have been reported to demonstrate an ultra-high quality factor [8]. Surface modes which have been studied extensively in literature [9–11], are an extreme example of heterostructure modes, in which the heterostructure is composed of one semi-infinite PC and one semi-infinite homogeneous medium [10]. The only thing we need is the replacement of homogeneous medium with the other PC. To favor the creation of guided modes at the interfaces of heterostructures, we require special PCs of heterostructures with much larger widths of absolute PBGs, because such PCs can then easily produce guided modes residing inside the wide PBGs. Zhou et al. [12] suggested that by rotating square cylinders in a square lattice, the widths of absolute PBGs could be significantly enlarged.

In this work, we confine ourselves to interface modes in the heterostructure consisting of two-dimensional (2D) semi-infinite lattices. The two square lattices are composed of circular and rotated square cylinders and the interface is assumed to be parallel to the y-axis of the lattice. Air square holes perforated in a homogeneous dielectric medium, while, the circular dielectric rods embedded in air background. Rotation of the square holes is introduced by θ, which is the inclined angle of the side of square holes against the x-axis (see Fig. 1(a)). The widest shared photonic band gap between two PCs can be obtained through θ. We have shown that using of an appropriate supercell is essential in obtaining the guided interface modes.

2. Formulae and model structures of heterostructures

The PCH is composed of two PCs with square symmetry shown in Fig. 1(a). The left PC consists of circular silicon rods embedded in air background while the right one is formed with rotated square air holes in a silicon background. Hereafter left and right PCs are called circular PC (CPC) and square PC (SPC), respectively. We used symmetric supercell consisting of N_c (odd number) and N_s (even number) complete unit cells from original PCs which were depicted in Fig. 1(b). Since, the fields of the interface modes decay exponentially in each side of interface and they become vanishingly small far enough from the interface, the requirement for an accurate computation of heterostructures modes is that all three regions in Fig. 1(b) are wide enough in order to ensure that the interface modes do not interact (overlap) with those of the neighboring supercells (see Ref. [10]).

It is well-known that, the eigenvalue equation for TM polarization can be written as [10]:

$$\sum_{\vec{G}'} \mu_{\vec{G}-\vec{G}'} \left[\left| \vec{k} + \vec{G} \right| \left| \vec{k} + \vec{G}' \right| \right] E\left(\vec{G}'\right) = \omega^2 / c^2 E\left(\vec{G}\right). \tag{1}$$

Here $\vec{G}$ and $\vec{G}'$ are the reciprocal vectors of the superstructure given by $\vec{G} = \frac{2\pi m_1}{L}\hat{x} + \frac{2\pi m_2}{a}\hat{y}$, where m_1 and m_2 are integer numbers.

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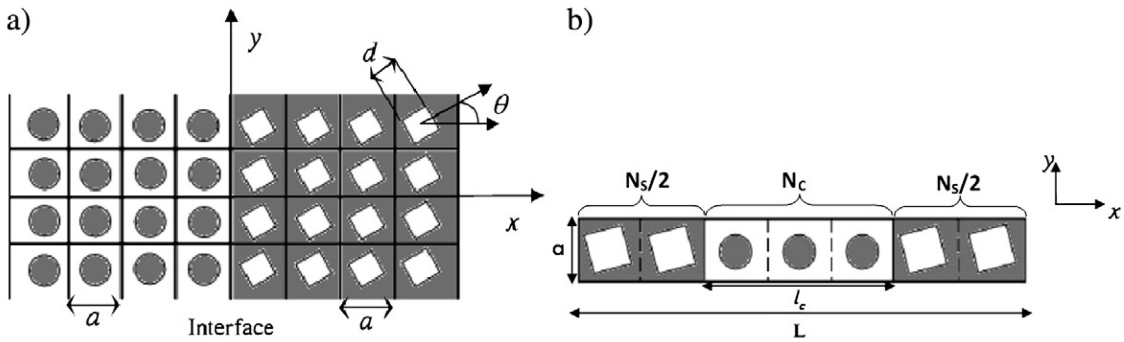

Fig. 1. (a) Cross section of the heterostructure composed of dielectric circular and air square cylinders in a square lattice. (b) Schematic representation of the supercell used in our calculations.

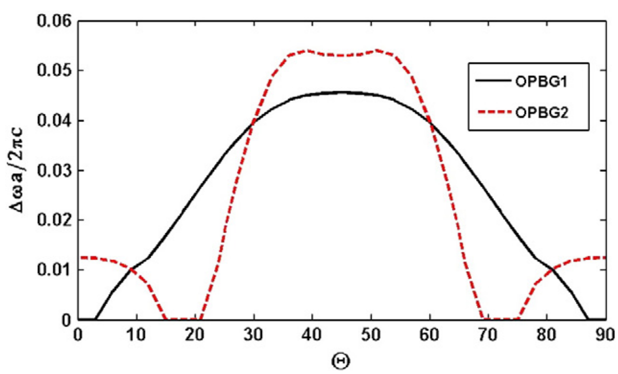

Fig. 2. Variation of the first two OPBGs versus rotating angle of the square holes.

$E(\vec{G})$ and $\mu(\vec{G})$ are the Fourier coefficient of electric field and inverse of dielectric function, respectively. $\mu(\vec{G})$ for our used supercell can be written as:

$$\mu_{\vec{G}} = \frac{1}{\varepsilon_b^s}\delta_{\vec{G},0} + \frac{l_c a}{A}\left(\frac{1}{\varepsilon_b^c}-\frac{1}{\varepsilon_b^s}\right)\frac{\sin G_x l_c/2}{G_x l_c/2} + 2f_c\left(\frac{1}{\varepsilon_a^c}-\frac{1}{\varepsilon_b^c}\right)\frac{J_1(GR)}{GR}S_c + f_s\left(\frac{1}{\varepsilon_a^s}-\frac{1}{\varepsilon_b^s}\right)\frac{\sin\tilde{G}_x d/2}{\tilde{G}_x d/2}\frac{\sin\tilde{G}_y d/2}{\tilde{G}_y d/2}S_s. \quad (2)$$

Here $\varepsilon_a^c(\varepsilon_a^s)$ and $\varepsilon_b^c(\varepsilon_b^s)$ are the dielectric constant of circular rods (square holes) and background of CPC (SPC). A, R and $J_1(x)$ are the supercell area, radius of circular rods and the first-kind Bessel function, respectively. Also, f_c, f_s, S_c and S_s are given by:

$$f_c = \pi R^2/A, \qquad f_s = d^2/A, \quad (3)$$

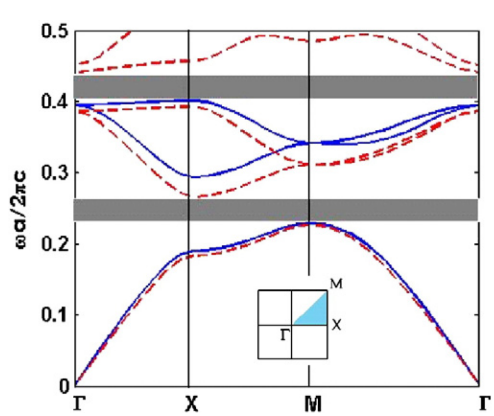

Fig. 3. The dashed (solid) lines show the band structure of the CPC (SPC for $\theta = 30$).

$$S_c = 1 + \sum_{k=1}^{(N_c-1)/2} 2\cos(kG_x a), \qquad S_s = 2\sum_{k=1}^{(N_s-1)/2}\cos(G_x(l_c + (2k-1)a)/2), \quad (4)$$

In Eq. (2) $\tilde{G}$ is related to G via:

$$\begin{pmatrix}\tilde{G}_x\\ \tilde{G}_y\end{pmatrix} = \begin{pmatrix}\cos(\theta) & \sin(\theta)\\ -\sin(\theta) & \cos(\theta)\end{pmatrix}\begin{pmatrix}G_x\\ G_y\end{pmatrix}. \quad (5)$$

The interface modes of the PCH can be obtained by solving Eq. (1) for an auxiliary periodic superstructure composed of the supercell.

3. Numerical results and analyses

It has been assumed that the CPC is made of silicon rods ($\varepsilon_a^c = 11.90$) with radius $R = 0.33a$ in air background, while the SPC is composed of square air holes in a silicon background with side of $d = 0.8a$. The primary vectors of this supercell are chosen by $\hat{a}_1 = L\hat{x}$ and $\hat{a}_2 = a\hat{y}$ where $L = (N_c + N_s)a$ is the length of the supercell and a is the lattice constant of square lattice. In our calculations we choose $N_c = 7$ and $N_s = 10$ which guarantee that the neighboring interface modes do not overlap and the number of plane waves in the expansion equals to $101 \times 19 = 1919$ that ensures sufficient convergence for the frequencies of interest. In order to study the interface modes which must be located at overlapping photonic band gap (OPBG) of the two PCs, we should have large OPBG. We have calculated band structure of CPC and non-rotated SPC. Our numerical results reveal that there is no overlaps between first PBG of the two

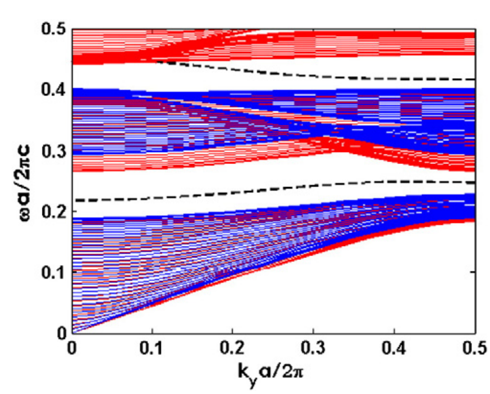

Fig. 4. Red (blue) region represents projected band structures of the SPC (CPC) and white regions show common PBG in which the interface modes are displayed by dashed line.